

**COMMUNICATION SYSTEM ARCHITECTURES FOR MISSIONS TO MARS<sup>1</sup>**  
**-A PRELIMINARY INVESTIGATION-**

Tien M. Nguyen, *IEEE Senior Member*, Sami M. Hinedi, *IEEE Senior Member*,  
Warren L. Martin, and Haiping Tsou, *IEEE Member*

**Jet Propulsion Laboratory**  
**California Institute of Technology**  
4800 Oak Grove Drive  
Pasadena, CA 91109

**ABSTRACT**

This paper presents various communication system architectures for Multiple-Link communications with Single Aperture (MULSA) ground station. The proposed architectures are capable of supporting a multiplicity of spacecraft that are within the beamwidth of a single ground station antenna simultaneously. Both short and long term proposals to address this scenario will be discussed. In addition, the paper also discusses the top-level system designs of the proposed architectures and attempts to identify the associated advantages and disadvantages for each system.

**1. INTRODUCTION**

Currently, there are several proposed future missions to Mars, namely, MarsNet and Mars Environmental Survey (MESUR)<sup>2</sup>, that are involved with a multiple spacecraft. MarsNet, (consists of 3 or 4 small landed stations) is a joint National Aeronautic Space Administration (NASA) and European Space Agency (ESA) mission which will complement the investigations of Mars conducted by MESUR network and the proposed launch date is January, 2001. On the other hand, the MESUR network comprises 16 small landing vehicles distributed over Martian surface to form a global network with the proposed launch dates are distributed as follows: 4 in 1999, 4 in 2001, and the final 8 in 2003. It is possible that the Deep Space Network (DSN), managed by the Jet Propulsion Laboratory (JPL) for NASA, will be asked to simultaneously support a multiplicity of spacecraft that are within a beamwidth of a single

<sup>1</sup>The research described in this paper was carried out at the Jet Propulsion Laboratory of the California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

<sup>2</sup>Warren L. Martin and Bruce R. Crow, "JPL DAP Planning-Office 410-Advanced Missions Program-Summaries of Missions Under Study," January 1993, an internal document, JPL, CA.

ground station antenna. This provides a unique opportunity to communicate with multiple spacecraft using a single antenna, as the latter results in maximum operational cost saving. For such occasions, one needs to identify alternative system architectures that are capable of tracking several spacecraft from a single earth station using a single earth-to-space link (uplink) and multiple space-to-earth links (downlinks). In order to identify accurately these architectures, one must define a set of requirements and constraints imposed on both spacecraft and ground station operational equipments. Given these defined requirements, one can then derive various architectures that will satisfy most of them. Since future NASA missions will require low cost, small size, low power consumption spacecraft telecommunication equipments, the proposed architectures must have also satisfied these requirements.

For the proposed missions to Mars, there are two classes of communications that the desired system needs to provide on the downlink. First is the simple one-way communication in which the downlink frequency can be derived from the spacecraft local oscillator, and the second is the two-way communication where the downlink frequency is derived coherently from the uplink. Usually, for deep space communications, coherent communication mode is preferred for navigation purpose along with best achievable system performance. For uplink communication, the MUSA scenarios have certain synergy with cellular systems [1-2]. In the later, the forward link employs multiplexing technique using orthogonal signals generated with Walsh functions [13] while the uplink for MUSA also employs multiplexing with unique word detection for compatibility with the current space communication standards [5]. The key challenge is on the downlink especially with coherent turnaround capability. The latter should be accomplished with mass-producible transponder with power efficient modulation, as opposed to spectrum efficient modulation employed in the cellular systems on the return link [1 and 13].

Recently, [3] have identified several system requirements that the DSN must provide for MUSA scenarios. These include (1) simultaneous telecommand, telemetry, ranging and Doppler data services, (2) support of radio science measurements, (3) a compatible relay orbiter interface if possible, (4) a simple spacecraft transponder design with no significant increase in cost or weight, (5) a capability for multi-

mission operations with optimum performance, and (6) conformance to the current international standards [4-5]. For short term proposed system architectures, requirements (4) and (6) are strictly enforced. This imposes further restrictions on both spacecraft and ground station equipments; namely, decoding of the command data using the currently available Command Detector **Unit** (CDU), minimum modification to the ground station receiving hardware, capability of receiving multiple carriers in the presence of simultaneous telemetry and ranging signals, and the cost of required modifications should be lower than multiple aperture solution. From these requirements, it is clear that the proposed architectures must be simple to meet the cost constraints but may not be able to meet system performance requirements. Hence, one can classify the proposed architectures into two categories: those that are suitable for short term solution and those for long term solution. This paper will discuss both short and long term solutions for MULSA scenarios.

## 2.. PROPOSED SYSTEM ARCHITECTURES FOR SHORT TERM SOLUTION

Currently, only two alternative architectures have been identified for short term solution. Both of these employ a single DSN station to support several spacecraft which are simultaneously within the same beamwidth of the single DSN antenna. Spacecraft discussed through out of this paper can be landers, orbiters, or any other of vehicle use in the Mars exploration missions. Both systems proposed in this section employ a single uplink but use different techniques for separating the downlink channels from each spacecraft. The first requires an Adjustable Turn Around Frequency Ratio (ATFR) on the spacecraft transponder<sup>3</sup>. The second system utilizes Subcarrier Frequency Division Multiplexing (SFDM) technique to separate the downlink channels [3].

### 2.1. ADJUSTABLE TURN AROUND FREQUENCY RATIO (ATFR)

Illustrated in Figure 1a is the proposed system architecture that employs the ATFR technique to separate the downlink channels. A detailed description of this system can be found in footnote 3.

<sup>3</sup>Warren L. Martin, "Minutes of First Meeting of DSN Single Aperture Multi-Link Team," April 15, 1994, JPL-IOM, 026 IOM94.WLM, an internal document, JPL, CA.

However, key features for this technique will be reiterated in this section for the sake of completeness. On the uplink, the telecommand signal is sent using a single, residual carrier RF frequency ( $f_c$ ) from a DSN earth station and this will be received simultaneously by all spacecraft which lie within the earth station antenna's beamwidth. A standard telecommand signal can be expressed mathematically as [4]

$$S_{UP}(t) = \sqrt{2P_{UP}} \cos(2\pi f_1 t + m_{up} d(t) \sin(2\pi f_{su} t)) \quad (1)$$

where  $P_{UP}$  is the uplink power,  $m_{up}$  denotes the uplink modulation index,  $f_1$  denotes the uplink frequency,  $d(t)$  is the telecommand data which is Non-Return-to Zero (NRZ) formatted, and  $f_{su}$  is the telecommand subcarrier frequency. All spacecraft lock to the uplink frequency  $f_1$  simultaneously. Packet telecommanding which conforms to the international standards recommended by the Consultative Committee for Space Data Systems (CCSDS) [4] is used to separate the command data on the uplink. Since the CCSDS telecommand format allows addressing of both spacecraft and instrument, only commands addressed to a specific spacecraft will be responded by that spacecraft. Command data is then routed to various subsystems whose address appears in the packet header.

To separate the downlink channels, this system requires an adjustable transponder turnaround frequency ratio. The current recommended coherent Turn Around Frequency Ratio (TFR or TAR) are fixed at 240/2.21 for 2 GHz band and 880/749 for 8 GHz band. To generate different downlink frequencies for  $N$  different spacecraft, it is necessary to vary the coherent TAR in such a way that the downlinks are coherent with the uplink frequency  $f_c$  with sufficient frequency separation to avoid the spectral overlap among the spacecraft when the Doppler shift is present. A standard downlink signal for each spacecraft employs PCM/PSK/PM modulation technique [4] which can be expressed mathematically as:

$$S_{Di}(t) = \sqrt{2P_{Di}} \cos(2\pi TAR_i f_1 t + m_{Di} d_i(t) P_i(t)); \text{ where } i = 1, 2, 3, \dots, N \quad (2)$$

where  $P_{Di}$  is the downlink power,  $m_{Di}$  denotes the downlink modulation index which is less than 90°,  $TAR_i$

denotes the  $\omega_{acrn}$  turnaround ratio,  $d_i(t)$  is the downlink data which is Non-Return-to Zero (NRZ) formatted, and  $P_i(t)$  is the telemetry subcarrier waveform which is squarewave for deep space missions and sinewave for near earth missions [4]. The subscript  $i$  in Eqn (2) denotes the  $i^{th}$  spacecraft. The spectrum of Eqn (2) is shown in Figure 1b. For missions with high telemetry data rates, the CCSDS recommends the downlink signal employs PCM/PM modulation technique without a subcarrier which is given by

$$S_{d_i}(t) = \sqrt{2P_d} \cos(2\pi T A R_i f_1 t + m_{d_i} d_i(t)); \quad i=1, 2, 3, \dots, N \quad (3)$$

where  $d_i(t)$  is the downlink data which is Bi-phase formatted [4]. Currently NRZ data format is also being considered for PCM/PM modulation technique [10]. Spectrum of Eqn (3) is illustrated in Figure 1c.

Since the downlink signal is modulated on different residual RF carrier frequency, this technique provide the best system performance in terms of Symbol Error Rate (SER). But to select various coherent downlink frequencies or various coherent TARs for deep space analog transponder is a challenging task [6]. Due to many different constraints, the number of coherent TAR available is finite and that, once the TAR is implemented in the spacecraft analog transponder it will be fixed for that particular mission. Therefore, mass production of several spacecraft transponders is not possible with this technique. However, with the advance in digital frequency synthesizer technology, it is possible to build a simple lightweight variable ratio digital transponder that meet the stringent deep space requirements on frequency stability, spurious emission and exciter bandwidth [7-8]. To further reduce the cost and weight of the transponder, one can combine the RF phase extraction and digitization in one unit such that the second RF portion can be eliminated [9]

## 2.2. SUBCARRIER FREQUENCY DIVISION MULTIPLEXING (SFDM)

A second short term solution that requires minimum hardware modifications to the current standard NASA transponders and DSN ground station is SFDM architecture. The uplink communication is the same as before but the downlink communication is modified as follows. Here, PCM/PSK/PM

modulation is employed with the modulation index set to  $90^\circ$  so that the carrier is fully suppressed and that various downlink telemetry signals can be put on various subcarriers at different subcarrier frequencies. The concept for this technique is shown in Figure 2a and the mathematical description for the downlink signal is

$$S_{Di}(t) = \sqrt{2P_{Di}} \cos(2\pi f_{Di}t + \frac{\pi}{2} d_i(t) P_i(t)); \quad i=1, 2, 3, \dots, N \quad (4)$$

where  $f_{Di}$  is a fixed downlink frequency and the definition for other parameters found in Eqn (4) can be found in Section 2.1.

Figure 2b shows a simplified block diagram for the SFDM architecture. The main advantages associated with this system are that it is compatible with the current DSN systems and some CCSDS standards with minor modifications required to current available spacecraft transponder and minor modifications to DSN ground station receivers. Modifications are required for the setting of the center and cut off frequencies of the RF filter implemented at the RF section of the spacecraft transmitter. Hence, mass production of spacecraft transponder is possible. However, there are inherent drawbacks for this technique. At low symbol Signal-to-Noise Ratio (SNR), this system is expected to perform poorer than ATFR system due to suppressed carrier tracking, and it also requires frequency optimization to avoid interference when the ranging is present.

### 3. PROPOSED SYSTEM ARCHITECTURES FOR LONG TERM SOLUTION

The proposed architectures for long term solution should outperform (in terms of system performance, spectrum efficiency, hardware complexity and number of supportable spacecraft) the short term solution but at the expense of major modifications to both spacecraft transponders and ground station receivers. Currently, one alternative mechanization has been identified, namely, PN Code Division Multiplexing (CDM) [11-12]. This utilizes various PN orthogonal codes to separate signal from the various spacecraft, and both of these architectures use suppressed carrier modulation schemes such as BPSK or QPSK. In the following, BPSK modulation scheme will be assumed. Furthermore, in this

proposed architecture, the uplink communications will be assumed to be identical to the short term solution.

### 3.1. PN CODE DIVISION MULTIPLEXING (CDM)

Figure 3 depicts a simplified block diagram for the CDM architecture. Here, all spacecraft transponders have a single, fixed T/R that will produce a fixed downlink RF carrier at frequency  $f_c$ . Before downlink telemetry data is modulated on the RF carrier, it is modulated and added to a PN code. Different encoders are used on each of the spacecraft such that they are orthogonal to one-another. PN codes are used to spread the spectrum and to make each signal uniquely detectable on the ground [11-12] and the mathematical expression of the downlink signal is defined as

$$S_{di}(t) = \sqrt{2P_{di}} d_i(t) PN_i(t) \cos(2\pi f_c t); i = 1, 2, 3, \dots, N \quad (5)$$

where  $PN_i(t)$  denotes the PN code for the  $i$ 'th spacecraft. Since this system employed suppressed carrier modulation, the system should also operate at low symbol SNR with increased background noise due to many codes occupying the same RF spectrum. Additionally, this technique requires a PN generator on board of the spacecraft and a PN demodulator on the DSN ground station. For optimum performance certain relationship between the PN code's "chip" rate, the telemetry data rate and the downlink frequency must be satisfied and this may add additional complexity on the flight hardware. Despite all these disadvantages associated with CDM technique, this provides the most RF spectrum efficient modulation technique that can support a large number of spacecraft.

## 4. COMPARISON OF ALTERNATIVE ARCHITECTURES

This section compares the various architectures proposed in the previous sections based on five different criteria, namely, hardware complexity onboard of the Spacecraft (S/C) and ground station receivers, system performance, the number of S/C can be accommodated, spectrum efficiency and system compatibility. The results of the comparison are summarized in Table 1. Table 1 shows that ATFR technique provides the best performance but it requires major modifications to S/C and ground station

hardwares. The SDFM technique requires no modification on S/C transponder hardware and minimum or no modification on the ground station hardware and provides good system performance and reasonable spectrum efficiency (depending on the data rate). On the other hand, CDM technique provides the worst performance in terms of SER but the best in terms of spectrum efficiency and maximum number of spacecraft accommodated but it requires significant modifications to both S/C and ground station hardwares.

#### S. CONCLUSIONS AND FUTURE WORK

Based on the investigation described above, it is possible that the DSN can support MULSA scenarios with minimum hardware modifications. However, the system performances for the proposed architectures are unknown, therefore, one can not assess the cost impact of these modifications on the S/C transponder and ground station receivers. This is an on-going research at JPL, the detailed on how these architectures behave under various system conditions along with the modification cost and maximum number of S/C that each architecture can support is under investigation.

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TABLE 1. COMPARISON OF VARIOUS SYSTEM ARCHITECTURES

Architecture	ATFR	SFDM	CDM	REMARK
Feature				
S/C Transponder Hardware Complexity	High	Very low	Low	Mass production may not be poss. for ATFR.
Ground Hardware complexity	Medium-High	Very Low	Medium	
System Performance	Excellent	Good	Poor	SER performance
# S/C can be Accommodated	Low for analog, Medium for digits Transponder	Medium	High	
Spectrum Efficiency	Low for PCM/PSK/PM - Medium for PCM/PM	Medium	High	For SFDM, data rate may be limited by subcar. frequency
Compatible with Current Standards	Not compatible with Earth stations	May Violate CCSDS Recommendation	yes	SFDM violates CCSDS Rec. for high data rates.

Figure 1a. ATFR System Architecture

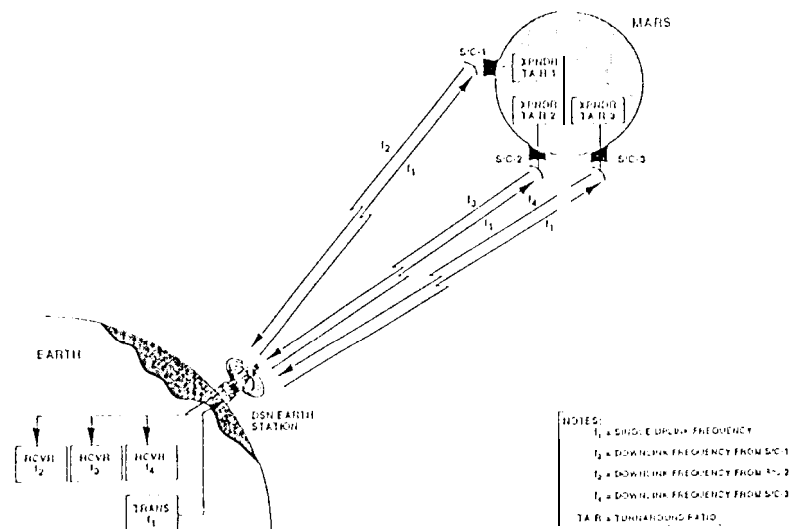
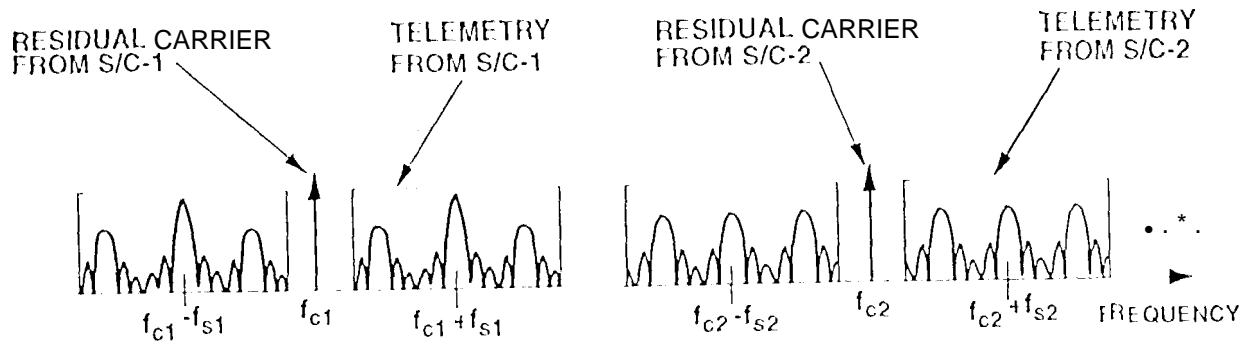


Figure 1 b. Spectrum of ATFR Signals With Sucaniers



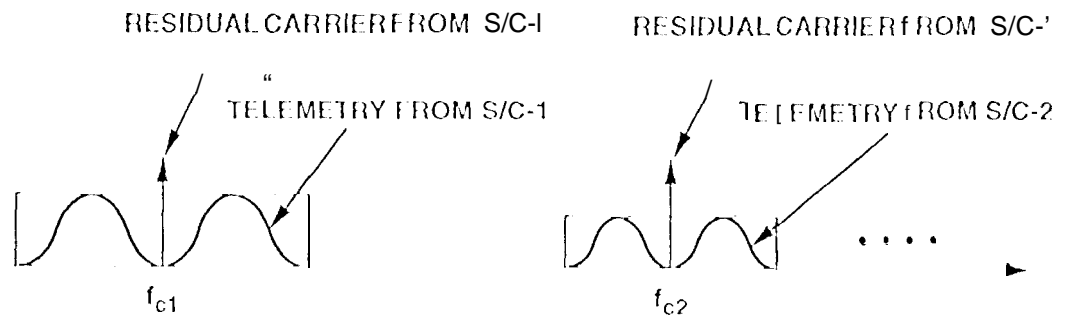
NOTES:

$f_{ci}$  = CARRIER FREQUENCY OF S/C- $i$ ,  $i = 1, 2, \dots$

$f_{si}$  = SUBCARRIER FREQUENCY OF S/C- $i$ ,  $i = 1, 2, \dots$

S/C = SPACECRAFT

Figure 1 c, Spectrum of ATFR Signals Without Subcarriers

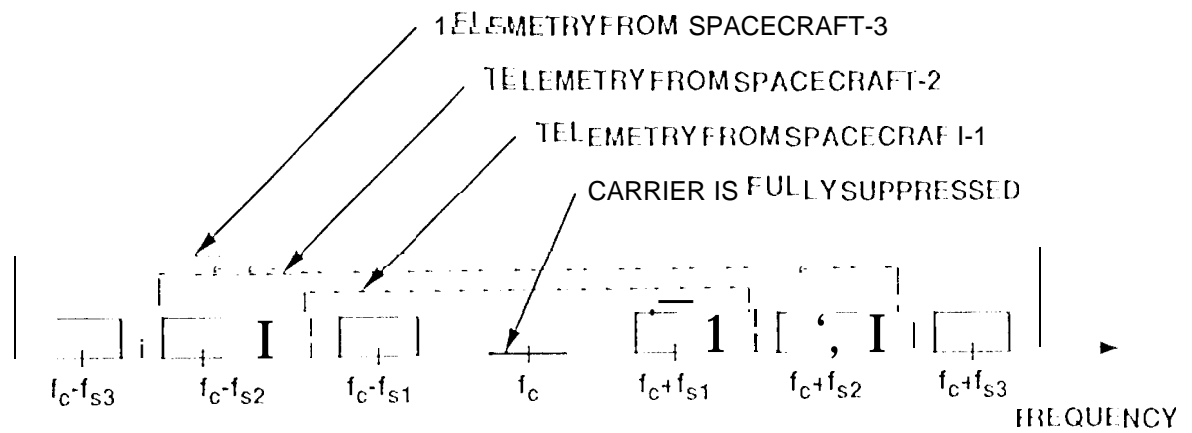


NOTES:

$f_{ci}$  = CARRIER FREQUENCY OF S/C- $i$ ,  $i = 1, 2, \dots$

S/C = SPACECRAFT

Figure 2a. Spectrum of SFDM Signals



NOTES:

$f_c$  = CARRIER FREQUENCY

$f_{si}$  = SUBCARRIER FREQUENCY,  $i = 1, 2, 3$

Figure 2b. SFDM System Architecture

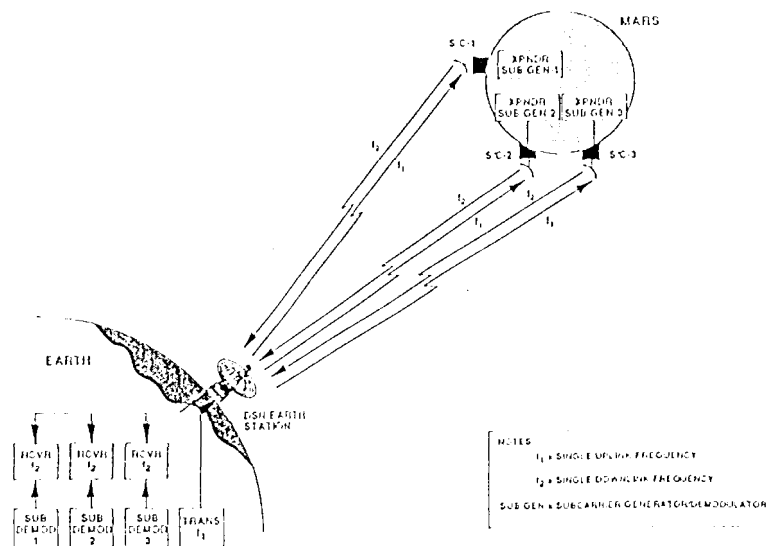


Figure 3. CDM System Architecture

